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PAIRING OF SUPERMASSIVE BLACK HOLES IN UNEQUAL-MASS GALAXY MERGERS

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ABSTRACT

We examine the pairing process of supermassive black holes (SMBHs) down to scales of 20-100 pc using a set of *N*-body/SPH simulations of binary mergers of disk galaxies with mass ratios of 1:4 and 1:10. Our numerical experiments are designed to represent merger events occurring at various cosmic epochs. The initial conditions of the encounters are consistent with the ΛCDM paradigm of structure formation, and the simulations include the effects of radiative cooling, star formation, and supernovae feedback. We find that the pairing of SMBHs depends sensitively on the amount of baryonic mass preserved in the center of the companion galaxies during the last phases of the merger. In particular, due to the combination of gasdynamics and star formation, we find that a pair of SMBHs can form efficiently in 1:10 minor mergers, provided that galaxies are relatively gas-rich (gas fractions of 30% of the disk mass) and that the mergers occur at relatively high redshift ($z \sim 3$), when dynamical friction timescales are shorter. Since 1:10 mergers are most common events during the assembly of galaxies, and mergers are more frequent at high redshift when galaxies are also more gas-rich, our results have positive implications for future gravitational wave experiments such as the Laser Interferometer Space Antenna.

Subject headings: black hole physics — cosmology: theory — galaxies: interactions — hydrodynamics — methods: numerical

1. INTRODUCTION

Compelling dynamical evidence indicates that supermassive black holes (SMBHs) with masses ranging from 10^6 to above 10^9 $M_\odot$ reside at the centers of most galactic spheroids (e.g., Ferrarese & Ford 2005). The masses of SMBHs correlate with various properties of their hosts, e.g. luminosity or mass (Magorrian & al. 1998; Häring & Rix 2004) and velocity dispersion (Ferrarese & Merritt 2000; Gebhardt & al. 2000). In the currently favored model for structure formation, the ΛCDM cosmology, galaxies grow hierarchically through mergers and accretion of smaller systems (e.g., White & Rees 1978). Thus, if more than one of the merging galaxies contained a SMBH, the presence of two or more SMBHs in their merger remnant will be almost inevitable during galaxy assembly (Begelman et al. 1980). However, it is unclear if the dynamical processes at play are efficient in forming a close SMBH pair with separations $\sim$ 10–100 pc, which may subsequently shrink to a bound binary, and eventually merge via gravitational wave radiation. Such black hole coalescence events are expected to give rise to gravitational wave bursts that should be detectable by the Laser Interferometer Space Antenna (LISA) (Vecchio 2004).

SMBH pairing has been shown to proceed quickly when both compact objects are hosted by steep stellar cusps approaching each other from close distances (Milosavljević & Merritt 2001), or when embedded in a circumnuclear gaseous disk under appropriate thermodynamic conditions (Mayer et al. 2007), but whether the large-scale merger can lead the SMBHs to such a favorable configuration is still a matter of debate. Previous studies found that, following a galaxy merger, the relative distance of the SMBHs in the remnant is very sensitive to the structure of the merging galaxies, and to their initial orbit (Governato et al. 1994). Kazantzidis & al. (2005) showed that pairing is efficient in equal-mass disk galaxy mergers with cosmologically relevant orbits, while the presence of a dissipative component is necessary for the pairing of SMBHs in 1:4 mergers. Other recent studies (e.g., Springel et al. 2005; Johansson et al. 2009) focused on the effect of energetic feedback from black hole accretion onto the surrounding galaxy, but were not designed to follow the orbital evolution of SMBHs. Substantially less effort has been devoted to examining the fate of SMBHs in minor mergers (but see Boylan-Kolchin & Ma 2007), which are much more frequent in ΛCDM cosmologies (Lacey & Cole 1993; Fakhouri & Ma 2008). Investigating the necessary conditions for SMBH pair formation in this regime is of primary importance for the search of gravitational waves and for SMBH demographics and activity.

In this Letter, we report on the efficiency of the SMBH pairing process using a set of *N*-body/SPH simulations of disk galaxy mergers, with mass ratios $q = 0.25$ and 0.1, constructed to represent mergers occurring at various cosmic epochs. The choice of the initial conditions, in particular the masses of the SMBHs, is such that the corresponding SMBH coalescence events would be detectable with LISA (Sesana et al. 2005).

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2. SIMULATION SET-UP

The galaxy models were initialized as three-component systems following the methodology outlined in Hernquist (1993). They comprise a Hernquist spherical stellar bulge (Hernquist 1990), an exponential disk with a gas mass fraction f_g, and an adiabatically contracted dark matter halo (Blumenthal et al. 1986) with an initial NFW profile (Navarro et al. 1996). A collisionless particle representing the SMBH was added at the center of each galaxy.

Our reference model is a Milky-Way type galaxy, with a virial velocity $V_{\rm vir}$ = 145 km/s, a disk mass fraction $M_d = 0.04 M_{\rm vir}$, and a bulge mass fraction $M_b = 0.008 M_{\rm vir}$. The mass of its central SMBH is $M_{\rm BH} = 2.7 \times 10^6$ M$_\odot$, consistent with the updated $M_{\rm BH} - M_{\rm bulge}$ relation (Häring & Rix 2004). The disk scale height and the bulge scale radius are $z_0 = 0.1 R_d$ and $a = 0.2 R_d$ respectively, R_d being the exponential disk scale length. R_d is determined following the model by Mo, Mao, & White (1998) (MMW hereafter), which yields disk galaxies lying on the Tully-Fisher relation. Models at redshift $z = 0$ were initialized with a halo concentration parameter $c = 12$ (Bullock et al. 2001). We also ran mergers with initial conditions rescaled to $z = 3$ according to MMW, keeping $V_{\rm vir}$ fixed, as expected for the progenitors of our $z = 0$ models (Li et al. 2007). Considering high-redshift mergers is crucial, because the merger rate increases with look-back time, and a large fraction of the gravitational wave signal from coalescences of SMBH binaries is predicted to originate from this cosmic epoch at the corresponding mass scale (Sesana et al. 2005; Volonteri et al. 2003). Following MMW, all masses, positions and softening lengths were rescaled by a factor $H(z=3)/H_0$, i.e. the ratio between the Hubble constant at $z = 3$ and its present-day value for a ΛCDM "concordance" cosmology (H_0 = 70 km s^{-1} Mpc^{-1}, $\Omega_{\rm m} = 0.3$, $\Omega_\Lambda = 0.7$). The halo concentration was chosen according to Bullock et al. (2001), $c = 3$. Satellite galaxies were initialized with the same structure, with the mass in each component being scaled down by q. The resulting SMBH pairs fall in the typical range of masses whose coalescences will be detectable with LISA (Sesana et al. 2005). We choose orbital parameters for the mergers that are common for merging halos in cosmological simulations (Benson 2005): the baricenters of the two galaxies were placed at a distance equal to the sum of their virial radii and set on parabolic orbits with pericentric distances of 20% the virial radius of the most massive halo. All mergers we considered were coplanar and prograde.

All simulations were performed with GASOLINE, a TreeSPH N-body code (Wadsley et al. 2004). We ran collisionless ("*dry*", with $f_g = 0$) and gasdynamical ("*wet*") mergers with the same gas fraction in the primary and secondary galaxies, either $f_g = 0.1$ or 0.3. In wet runs, atomic gas cooling was allowed; star formation (SF) was treated according to Stinson et al. (2006). Gas particles are eligible to form stars if their density exceeds 0.1 cm^{-3} and their temperature drops below 1.5×10^4 K, and the energy deposited by a Type-II supernova on the surrounding gas is 4×10^{50} erg. With this choice of parameters our blast-wave feedback model was shown to produce realistic galaxies in cosmological simulations (Governato et al. 2007). A summary of our set of simulations is presented in Table 1.

In each galaxy (except for a very high-resolution test, see 3.1), we employed 10^6 particles for the halo, and, initially, 2×10^5 star particles and 10^5 gas particles, when included. The force softening was 100 pc in our reference model, scaled down by $q^{1/3}$ in the satellites, and by $H(z)/H_0$ in high-z runs, yielding a force resolution of ~ 20 pc in the satellite galaxy for $q = 0.1$ at $z = 3$. With such a high particle number, the masses of star particles in the satellite is an order of magnitude lower than $M_{\rm BH}$, ensuring that SMBH dynamics is not affected by spurious two-body collisions. In what follows, we define two SMBHs as a "pair" if their relative orbit shrinks down to a separation equal to twice the softening. From these distances, a SMBH binary may form in ~ 1 Myr (Mayer et al. 2007).

TABLE 1
SUMMARY OF SIMULATIONS

q	SF	f_g	z	BH final distance[a]
0.25	no	0	0	2 – 4 kpc
0.25	yes	0.1	0	200 pc
0.1	no	0	3	1 – 6 kpc
0.1 (hi-res)	no	0	3	1 – 5 kpc
0.1	yes	0.1	3	400 pc
0.1	yes	0.3	3	70 pc

[a] When possible, estimates of pericenter and apocenter of the orbit of the lighter SMBHs inside the merger remnant are given.

3. RESULTS

3.1. *Collisionless Mergers*

In collisionless runs, the satellite is not able to dissipate energy gained through tidal shocks at pericentric passages (Gnedin et al. 1999; Taffoni et al. 2003). For $q = 0.25$, dynamical friction on the dark matter halo of the more massive galaxy is efficient, and the satellite sinks down to a few ~ 10 kpc from the center after 3 orbits. At that point the central density of the satellite has decreased considerably because of tidal heating (Kazantzidis et al. 2004). Its innermost region is then tidally disrupted, leaving the small SMBH at a distance of a few kiloparsecs. The dynamical friction timescale has now greatly increased, because the mass of the small "naked" SMBH is orders of magnitude lower than that of the satellite's core that once surrounded it. No pair is formed, and the smaller SMBH is left wandering a few kiloparsecs away from the center of the remnant (Fig. 1). We note that estimating correctly the dynamical friction timescale of the SMBH from the simulation is not trivial in this regime, because the dark matter component is still dynamically important at kiloparsec distances from the center of the remnant. Even at high resolution, the mass of the dark matter particles of the primary galaxy is comparable with that of the SMBH, hence dynamical friction could be altered by discreteness effects. However, the dynamical friction timescale needed for the "naked" SMBH to reach the center of the remnant can be estimated using Chandrasekhar's formula (Colpi et al. 1999), and it turns out to be longer than a Hubble time. Hence we conclude that the two SMBHs will not form a pair.

In the $q = 0.1$ case, dynamical friction is rather ineffective. The sinking time for the satellite is longer than a Hubble time for a $z = 0$ merger, owing to the low initial mass of the satellite and to mass loss due to tidal stripping (Colpi et al. 1999). However, since mergers are much more common at higher redshift, when orbital times are shorter by a factor $H(z)/H_0$, we performed a $q = 0.1$ merger starting at $z = 3$ (see §2), an epoch at which these SMBH pairs are predicted to be most typical. This is completed in ~ 2.5 Gyr. Similarly to the $q = 0.25$ case, a wandering SMBH is left at several kiloparsecs from the center of the primary (Fig. 1). In order to check that the tidal disruption of the core was not affected by numerical

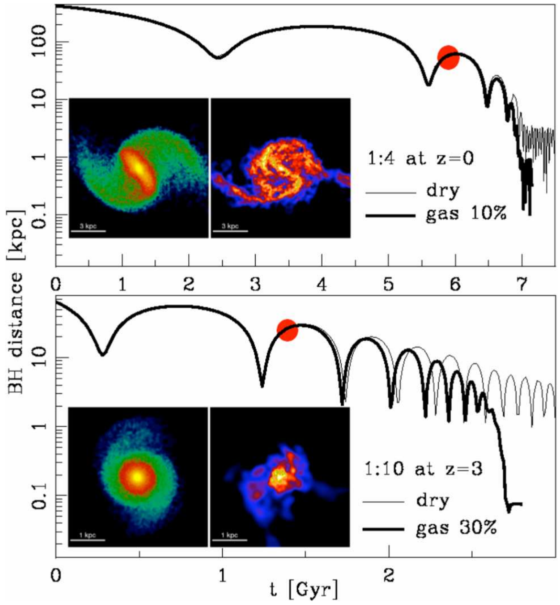

FIG. 1.— Separation of SMBHs as a function of time in four of our simulations. *Upper panel*: SMBH distance in $q = 0.25$ mergers; the thin and thick lines refer to the dry and wet cases, respectively. The inset shows the color-coded density of stars (*left*) and gas (*right*) for the wet case at $t = 5.75$ Gyr (marked in red on the curve); each image is 12 kpc on a side, and colors code the range $10^{-2} - 1$ $M_{\odot}$ pc^{-3} for stars, and $10^{-3} - 10^{-1}$ $M_{\odot}$ pc^{-3} for the gas. *Lower panel*: SMBH distance for $q = 0.1$, $z = 3$; the thin and thick line refer to the dry and $f_g = 0.3$ cases, respectively. The inset shows density maps at $t = 1.35$ Gyr for the $f_g = 0.3$ case; images are 4 kpc on a side (color coding as in upper panel).

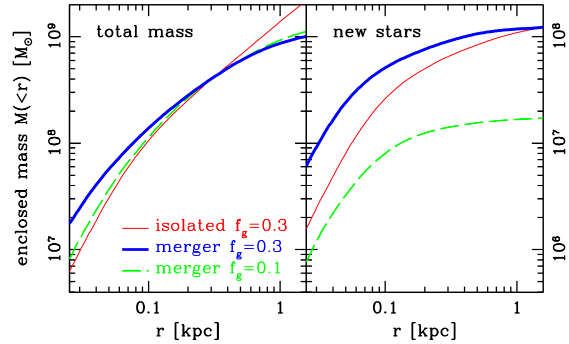

FIG. 2.— Cumulative bound mass profiles of $z = 3$, $q = 0.1$ satellites. Thin red lines refer to the $f_g = 0.3$ satellite in isolation, thick blue lines to the $f_g = 0.3$ merging satellite, and dashed green lines to the merging $f_g = 0.1$. All data refer to the third apocenter, or equivalent time in isolation ($t = 1.8$ Gyr). *Left panel*: total bound mass profiles. The more gas-rich satellite develops a higher concentration during the merger, compared to the other cases. Tidal truncation and gas removal cause a factor of ~ 2 difference in mass at 2 kpc between isolation and merging cases. *Right panel*: bound mass in stars formed after the start of the simulation. The total amount of stars formed depends roughly only on the initial f_g, but SF is more localized in the center during the merger because of tidal forces. The more gas-rich merging satellite undergoes the strongest central SF burst, developing a higher central density.

heating, we ran the same merger with a 5 times higher mass resolution in the stellar component of both galaxies, and correspondingly higher force resolution; no significant difference in the SMBH orbit was found (Tab. 1). Therefore, even in this case the two SMBHs do not form a pair.

3.2. *Dissipational Mergers with Star Formation*

The presence of a star-forming gaseous component crucially affects the orbital decay of the SMBH via its dynamical response to tidal forces and torques.

The orbits of dry and wet, $q = 0.25$ mergers differ only after the first couple of orbits ($\sim$ 6 Gyr, see Fig. 1). At second pericenter, tidal forces excite a strong bar instability in the satellite. Dissipation in the gas and torques exerted by the stellar bar onto the gas drive a gaseous inflow toward the center of the satellite (see inset in Fig. 1), increasing the central star formation rate by a factor of 3. Thus, the potential well of the satellite deepens, ensuring resilience of its central part to tidal stripping and shocks even when it plunges near the center of the primary. As a consequence, the small SMBH continues to sink fast, because it remains embedded in the massive core of the satellite. A pair of SMBHs is formed in this case, confirming previous results (Kazantzidis & al. 2005).

In $q = 0.1$, $z = 3$ wet mergers, both $f_g = 0.1$ and 0.3 were employed; the latter should be a more realistic assumption, since disk galaxies at $z = 3$ are believed to have a higher gas mass fraction (e.g., Franx et al. 2008). In these cases, star formation and supernovae feedback affect the structure of the interstellar medium (ISM) in the disks quite dramatically (see also Governato et al. 2007). The disks develop a clumpy and irregular multi-phase structure, and turbulent velocities of the gas become a significant fraction (30%) of the circular velocity in this mass range ($V_{vir} = 64$ km s^{-1}). Star formation in the center of the satellite is enhanced compared to the same model evolved in isolation, even though the star formation rate integrated over the whole galaxy is unchanged (see Fig. 2) The concentrated star formation and the turbulent motions of the gas stabilize the disks against bar instability (see inset in Fig. 1). In the absence of bar-driven torques, the strong gaseous inflow seen for higher-mass objects ($q = 0.25$) does not happen for $q = 0.1$. Yet, tidal torques drive some gas towards the center, explaining the enhanced central star formation (Fig. 2). During the first three orbits, the $f_g = 0.1$ case preserves its initial central density owing to the mild mass inflow, rather than lowering it as in the collisionless case, while the $f_g = 0.3$ satellite develops a steeper *stellar* cusp. Once the satellites go through the second pericentric passage, their ISM is prone to ram pressure stripping by the gas disk of the primary galaxy, outside the ram pressure stripping radius (Marcolini et al. 2003). Nearly 90% of the gas is swept away when they first enter the disk of the primary, while what remains is stripped during the next orbit: at $t = 2$ Gyr, the satellites have lost all their gas content, even in their central region. From this point onward, the satellite with initial $f_g = 0.3$ is a *cuspy, gas-poor object*, subject to dynamical friction in the stellar and gaseous background. Its sinking is relatively fast because the steeper stellar density profile implies a larger bound mass, enhancing dynamical friction relative to the dry merger case. Moreover, its response to tidal shocks is nearly adiabatic (Gnedin et al. 1999), preserving it from tidal disruption. On the contrary, the satellite of the $f_g = 0.1$ run undergoes a slower decay because of the lower bound mass. It then experiences a higher number of tidal shocks at pericentric passages which further decrease its density, until its complete disruption. As a consequence, the $f_g = 0.3$ merger leaves the lighter SMBH at 70 pc from the more massive one (Fig. 1, Tab. 1) in a gas-rich environment, where the dynamical friction timescale for the SMBH to sink to the center, based on Chandrasekhar's formula, is very short (< 1 Gyr). Instead, in the $f_g = 0.1$ case the final distance of the SMBHs is ~ 400 pc; at such separations the dynamical friction timescale is of a few billion years. Hence the pairing will occur within one Hubble time in both cases, but will be considerably faster in the $f_g = 0.3$ case.

4. DISCUSSION AND CONCLUSIONS

Our results show that the formation of a SMBH pair in unequal-mass mergers of disk galaxies is very sensitive to the details of the physical processes involved. None of the collisionless cases we studied led to SMBH pairing: tidal shocks progressively lower the density in the satellite until it dissolves, leaving a wandering SMBH in the remnant. The inclusion of gas dynamics and SF changes significantly the outcome of the merger. For higher mass ratios ($q = 0.25$) at $z = 0$, bar instabilities funnel gas to the center of the satellite, steepening its potential well and allowing its survival to tidal disruption down to the center of the primary. Therefore, in this case the presence of a dissipative component is necessary and sufficient to pair the SMBHs at ~ 200 pc scales, creating favorable conditions for the formation of a binary. The smaller satellites here considered ($q = 0.1$, $z = 3$) are more strongly affected by both internal SF and the gasdynamical interaction between their ISM and that of the primary galaxy. Torques in the early stages of the merger are funnelling the gas to the center less efficiently, due to the absence of a stellar bar and the stabilizing effect of turbulence. As a result, ram pressure strips away all of the ISM of the satellite. If satellites develop a higher central stellar density by rapidly converting their gas into stars before ram pressure removes it, they can retain enough bound mass to ensure the pairing of the two SMBHs. Gas-rich satellites ($f_{\rm g} = 0.3$) undergo a stronger burst of SF during the first orbits, and therefore meet this requirement better than $f_{\rm g} = 0.1$ satellites. Yet in both cases the central density of the cusp remains high enough to permit its survival, allowing the pairing of the two SMBHs within a Hubble time.

The pairing of the two SMBHs takes less than 1 Gyr in the gas rich systems that should be common at $z = 3$. Therefore, if the $M_{\rm BH} - M_{\rm bulge}$ relation approximately holds at $z = 3$ as in the local Universe, the galaxies here considered should lead to the formation of representative SMBH pairs at such cosmic epochs (Volonteri et al. 2003). These pairs are also expected to contribute significantly to the high-z gravitational wave signal in the LISA band (Sesana et al. 2005). Since we show that gas-dynamical processes allow such an efficient pairing of the SMBHs, the results of this *Letter* strengthens the case for the observability of these coalescence events. On the other hand, we show that the timing between galaxy mergers and mergers of their SMBHs is sensitive to the gaseous content of the merging galaxies. Hence, SMBH coalescence events do not necessarily trace galaxy mergers directly. This will have important implications on the interpretation of the LISA data stream.

We note that the orbital evolution of the SMBH pairs, in the dynamical range considered here, has only a weak dependence on the masses of the two SMBHs. As shown in Figure 2, the stellar mass enclosed inside two softening lengths from the center of our galaxy models (hence close to our resolution limit) already exceeds $M_{\rm BH}$ by more than an order of magnitude. This is the effective mass that determines how quickly the SMBHs will sink. Therefore, lowering $M_{\rm BH}$ or increasing it by up to an order of magnitude would have no effect on sinking timescales *before* the disruption of the satellite. Instead, *after* disruption, the analytic estimate for the dynamical friction timescale of the naked SMBH would change linearly with $M_{\rm BH}$. Similarly, if nuclear star clusters with masses $\sim 10\, M_{\rm BH}$ (Wehner & Harris 2006; Ferrarese & al. 2006) were present around the SMBHs, their sinking timescales would still be longer than a Hubble time in our dry mergers, where the final SMBH separation exceeds 1 kpc, while the pairing would now occur in well below a Gyr in *all* our wet mergers. Hence, either a larger $M_{\rm BH}$ or the presence of a nuclear star cluster would enhance even further the difference between dry and wet mergers.

Lastly, a general limitation of our simulations is that they lack gas accretion onto the SMBHs and associated energy feedback. Additional heating from the active SMBH should reduce the binding energy of the gas, making it more susceptible to stripping processes, and perhaps inhibiting the formation of a steep stellar cusp. This would reduce the efficiency of the pairing process, but the effect will strongly depend on when the SMBH becomes active during the merger. Although it is unlikely that these effects will change the overall picture presented in this Letter, they will have to be explored in a forthcoming paper.

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